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Laurence J. Heidelberg and David M. Elliott
Glenn Research Center, Cleveland, Ohio

June 2000

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A Comparison of Measured Tone Modes for Two Low Noise Propulsion Fans

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ABSTRACT

The acoustic modes for two low tip speed propulsion fans were measured to examine the effects of fan tip speed, at constant pressure ratio. A continuously rotating microphone method was used that provided the complete modal structure (circumferencial and radial order) at the fundamental and second harmonic of the blade passing tone as well as most of the third harmonic modes. The fans are compared in terms of their rotor/stator interaction modal power, and total tone power. It was hoped that the lower tip speed might produce less noise. This was not the case. The higher tip speed fan, at both takeoff and cutback speeds, had lower tone and interaction levels. This could be an indication that the higher aerodynamic loading required to produce the same pressure ratio for the lower tip speed fan resulted in a greater velocity deficit in the blade wakes and thus more noise. Results consistent with expected rotor transmission effects were noted in the inlet modal structures of both fans.

INTRODUCTION

The goal of the NASA Noise Reduction Element of the Advanced Subsonic Technology Program is to reduce the noise level of aircraft by a cumulative 30 dB relative to 1992 technology, by the end of the decade. This requires a 10 dB reduction in each of the three certification points where noise is measured (takeoff, sideline, and approach).

As part of this effort, two, low noise fans, designed with very low tip speeds, were tested in the NASA, Glenn 9' x 15' Low Speed Wind Tunnel. Both farfield and in duct acoustic data were obtained. Only the in duct tone mode measurements will be presented in this paper. The farfield results are presented in references 1, and 2. The 22-inch diameter fans tested were designed by Pratt & Whitney Division of United Technologies. The fan designated Fan 1 has a tip speed of 840 ft/sec at takeoff while Fan 2 has a still lower speed of 756 ft/sec. Both fans were designed to have the same pressure ratio (1.284) at these conditions. One of the objectives in testing these fans was to determine if a design tip speed as low as Fan 2 could produce further noise reduction.

APPARATUS AND PROCEDURE

Fan Models

One of the design intents for these fans is to evaluate the potential for fan noise reduction by lowering tip speed. Both Fan 1, and Fan 2 are 22 inches in diameter and have 18 rotor blades. Both have stator vane counts that cutoff the Blade Passing Frequency (BPF) tone interactions. The fan stage designs for Fan 1 and Fan 2 can be found in references 3 and 4, respectively. Table 1 shows the fan design parameters for both fans. The most important difference between the fans is the tip speed. At takeoff, both fans have the same pressure ratio but Fan 2 has a 10 percent lower tip speed. This lower speed results in a higher blade aerodynamic loading for Fan 2. In addition, Fan 2 has a higher vane number than Fan 1. This, when combined with the lower speed results in a cutoff 2BPF tone at approach for Fan 2.

Mode Measurements

A continuously rotating microphone technique described in Refs. 5 and 6 was used. A photograph of the rotating rake system installed on the fan inlet is shown in figure 1. The same system installed in the fan exhaust is shown in figure 2. This rotating measuring system turns at exactly 1/200 of the fan speed as if it were geared to the fan shaft. In the rotating frame of reference, each spinning order (circumferential order) is Doppler shifted inversely proportional to its spin rate. Thus, each circumferential order is separated by 0.005 shaft orders in frequency. The radial order is determined by a least squares curve fit of to the Bessel pressure profiles of all cuton radial orders plus the first cutoff order to the measured complex radial profile. In order to resolve the highest radial order that can propagate in the inlet, 12 radial measurements were used, while only 8 were needed in the

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exhaust. These microphone signals are brought across the rotating frame by FM telemetry.

Several improvements in this mode measurement technique have been made since its first implementation reported in Refs. 7 and 8. These improvements were developed during tests on a large low speed fan rig (Active Noise Control Fan - ANCF). One of these improvements was the installation of windscreens over the microphones to lower self-noise, thus improving signal to noise ratio. A 10 dB lowering of the noise floor was observed in the inlet of ANCF using a windscreen. These screens are made of an open cell aluminum foam that has negligible acoustic attenuation at frequencies below 15 kHz. Another improvement was the installation of additional foam shields on the exhaust rake to attenuate the effects of the rotor wakes and their interactions with the vanes (vortical waves) on the microphones. The inlet rake and windscreen is shown in figure 3 and the exhaust rake and screens are shown in figure 4. The idea behind the side shields on either side of the microphone rake is to reduce the effect of the rotor wakes and their interactions on the microphones. This is necessary since these non-acoustic waves have the same circumferential order as the acoustic waves. Since the microphones act as dynamic total pressure probes, they can sense these non-acoustic waves resulting in contamination of the acoustic signals.

Test Conditions

Both fans where operated at six different speeds that include the approach, cutback, and takeoff conditions. The fan models were run in the NASA, Glenn 9' x 15' Low Speed Wind Tunnel at a Mach Number of 0.1. Fan 2 was tested at a Mach Number of 0.2 during exhaust mode measurements to better compensate for the change in fan operating line caused by rake blockage. In addition, both fans used a slightly larger nozzle exit area to compensate for rake blockage. Both fans were tested in the hard wall (no acoustic treatment) configuration. The nacelle and flow path for both fans was the same, and is shown in figure 5. Although the blade stagger angle for these fans is adjustable, the fans were run at the takeoff setting for all testing.

The locations of the mode measurement planes are also shown in figure 5. The inlet measurements were taken at the throat (minimum diameter). The exhaust measurements were taken just inside the nozzle exit.

RESULTS AND DISCUSSION

The complete modal structure (circumferential and radial orders) for BPF and 2BPF as well as selected 3BPF modes were measured for Fan 1 and Fan 2. Both Inlet and exhaust duct modes are presented in terms of PWL referenced to 10^{-12} watts. The 2BPF modes will be discussed first and in more detail since the BPF, rotor/stator interaction is cutoff for both fans.

Modal Structure

Figure 6 shows this structure for Fan 1 and 2 at 2BPF at approach power. This figure portrays the modes in the form of a 3-D bar graph, with the mode power plotted against both circumferential (m) and radial (n) orders. The back row sums all the radials in each m order. The inlet and exhaust are dominated by the expected (Tyler-Sofrin) rotor/stator interaction order, m=-9 for Fan 1. The exhaust interaction is more than 12 dB higher than the inlet. The two radial orders of the m=-9 have similar levels in both the inlet and exhaust. The levels of modes extraneous to the rotor/stator interaction are very low, particularly in the exhaust. This is an indication that the fan installation is very clean (low inlet distortion, uniform tip clearance, etc.). The modal structure for Fan 2, shown on the right side of figure 6, shows no interaction modes. The interaction m order is cutoff at approach power. This is a result of the absolute value of the m order being high, m =-15 and the lower rotor speed of Fan 2. All the modes for fan 2 are extraneous and are roughly similar in level to the extraneous modes of Fan 1. Included in the figure are the total tone PWL, for each fan and measuring location. The tone PWL is calculated by summing of the PWL for each mode. Fan 2 is quieter than Fan 1 by 6dB in the inlet and almost 20 dB in the exhaust, mostly due to the interaction order being cutoff.

Figure 7 compares the modal structure for Fans 1 and 2 at 2BPF at takeoff power. Here the modal structure is dominated by the rotor/stator interaction with the exception of Fan 1 in the inlet. Although the inlet of Fan 1 has an interaction m order that is the single largest order, the extraneous modes control the total tone PWL. The Fan 2 interaction of m=-15 that was cutoff at approach power is now cuton and higher than the interaction of Fan 1. This results in Fan 1 being quieter than Fan 2 in terms of tone PWL by 9.4 dB in the Inlet and 3.4 dB in the exhaust. Differences in the extraneous modes between the two fans are not so different as to make interference with the comparison between fans, but differences in extraneous modes between the inlet and exhaust show trends that are more significant. There are larger and more numerous positive modes (co-rotating) in the inlet while the exhaust is more balanced. This may be a result of the negative (counter-rotating) modes suffering transmission loss through the rotor. Designers take advantage of this rotor transmission effect by selecting a stator vane count that results in negative interaction m orders, to reduced inlet levels. Another feature observed in the data is the low levels of radial order 0 (n=0) in the inlet for both fans. Generally, it has been observed that radial order zero has some of the highest levels and where there are a large number of radials cuton as in figure 7 (takeoff), the highest radials have low levels. Radial orders above five usually have levels near or below the noise floor of the data. This has been observed in this paper, in unpublished data, and reference 5. Here again, the low levels of radial order 0 in the inlet may be related to rotor transmission effects. These fans have high blade passage Mach numbers at takeoff and the Mach Number increases with radius up to about 80 percent of span. Almost all radial modes of order 0 carry their maximum pressure at outer wall (blade tip). This might lead to these modes suffering higher transmission loss than other modes.

The BPF m order results for Fans 1 and 2 are shown in figure 8. For brevity, this figure shows only the PWL in the m order, the sum of the radial modes in each m order. There are no interaction orders present for either fan at BPF; thus, all modes are extraneous. These modes can be caused by rotor / inlet distortion, variations in rotor tip clearance, etc. and are usually generated by the rotor. The BPF levels are generally lower than 2BPF (previous two figures) due to this lack of interaction modes. One exception to this is Fan 2, at approach in the exhaust, where they are the same, 95.7 dB. It should be remembered that Fan 2 has no 2BPF interaction at approach. Fan 2 appears to have lower BPF levels than Fan 1 especially at takeoff in the exhaust. This might indicate a better fit of parts in the inlet and more uniform tip clearance for Fan 2. There is no trend for the positive modes to predominate as in the 2BPF modes. This may be due to the rotor being the noise source and thus rotor transmission is not an issue.

Variation of Interaction and total tone power with speed

The 2BPF interaction and total tone power level, as a function of speed, for Fans 1 and 2 is shown in figure 9. Both the inlet and exhaust power for Fan 1are shown in figure 9a). The exhaust power is much higher than the inlet. Fan 1 exhaust total power is controlled by the interaction, m =-9, as is evident by the total power being only slightly higher than the interaction power. The inlet is controlled by the extraneous modes except at approach speed. The exhaust power increases with speed as would be expected. The inlet power does not change much with speed and actually decreases with speed above the takeoff. This type of behavior of inlet power has been observed in unpublished data for another fan. A possible explanation for flat or decreasing power with speed is a high rotor transmission loss at the high Mach numbers in the rotor blade passages corresponding to takeoff power.

Fan 2, shown in figure 9b) has no interaction power at approach speed because this mode is cutoff and thus the tone PWL is lower than Fan 1 in both the inlet and exhaust. Once the interaction mode is cuton, the exhaust power is much higher than the inlet. As in Fan 1, Fan 2 shows the exhaust totally controlled by the interaction mode, m=-15 at speeds above cuton. Unlike Fan 1, the inlet of Fan 2 is controlled by the interaction mode at speeds above cuton. This is primarily due to the higher level of the interaction mode in Fan 2.

A summary comparison of both fans is shown in figure 10. Here the levels of the 2BPF total tone power and the interaction mode power are shown for the rating conditions. Fan 2 shows lower tone levels only at approach speed and at all other conditions has higher tone levels than Fan 1. Although Fan 2 only has an advantage over Fan 1 at approach, it is dramatic one in the exhaust where the difference is 19 dB. Figure 10 b) shows a comparison of the exhaust power levels including the farfield power for the 2BPF tone from 70° to 158° from the inlet axis. Exhaust power levels for 2BPF are much higher then in the inlet. In one case (Fan 1 interaction), the difference is 25 dB. These highly dominant exhaust levels result in much of the farfield angles, that would normally be controlled by the inlet, to instead be exhaust controlled. This makes the exhaust comparisons more important than inlet comparisons. The farfield power was added to this figure just to see if the same trends observed in-duct is seen in the farfield. The farfield power should be compared to the total tone power in duct since it represents all modes. Both in-duct and farfield power show the same trends when comparing Fans 1 and 2, with the farfield averaging about 3 dB lower. There are many possible reasons for differences between in-duct and farfield power, a few of which are: the farfield power not integrated over the full range of emission angles, variations in azimuthal directivity, and duct termination reflections.

The 3BPF interaction modes for both Fans 1 and 2 are shown in figure 11 as a function of speed. The total tone powers are not available here because the number of radial measuring stations is insufficient to resolve the high number of radial modes cuton at these frequencies. Fan 1 has 2 m orders cuton, m=9 and –36. Where m=-36 is above the noise floor it is shown. In the exhaust, the sum of both modes is shown. Fan 2 has only one m order cut on, m=3. Fan 2 is quieter at approach especially in the exhaust, while both fans have similar levels at takeoff. An interesting observation for Fan 1 is that the 3BPF levels are higher than 2BPF in the inlet for most of the speed range (see fig.9).

CONCLUDING REMARKS

Fan 1, the higher tip speed design appears to be quieter for the 2 and 3BPF interaction tones and total tone power at speeds of cut back and above. This may indicate that a limit has been reached in lowering fan speed, at constant pressure ratio, to achieve low noise. The very high aerodynamic loading on the Fan 2 blades, to achieve the same pressure ratio as Fan 1, may have caused their wake velocity deficits to increase disproportional to the benefit of the lower tip speed. This begs the questions: 1) Does interaction noises inherently increase at tip speeds below those of Fan 1? 2) Is there something unique in the Fan 2 design that is responsible for an increase in noise? The second question is posed because a boundary layer instability (location of transition to turbulent flow) was noticed during performance testing of Fan 2. An examination of blade wake data for Fans 1 and 2 might help answer these questions, as well as running Fan 2 with the same vane count as Fan 1, but this is beyond the scope of this investigation.

The mode data in the inlet may indicate that rotor transmission plays an important role. The difficulty of counter-rotating spinning orders passing through the rotor, as well as high rotor blade passage Mach number at takeoff power may strongly influence inlet noise.

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Table 1. Fan Design Parameters

Fan Parameter	Fan 1	Fan 2
Pressure Ratio		
Takeoff	1.284	1.284
Cutback	1.209	1.209
Approach	1.077	1.077
Corrected Tip Speed (ft/sec)		
Takeoff	840	756
Cutback	723	667
Approach	480	425
Corrected rpm		
Takeoff	8750	7875
Cutback	7525	6950
Approach	5425	4425
Bypass Ratio - Cruise	13.3	13.3
Blade Number	18	18
Vane Number	45	51
2BPF Interaction m order	-9	-15
Hub/ Tip	0.426	0.426
Diameter (in)	22.0	22.0

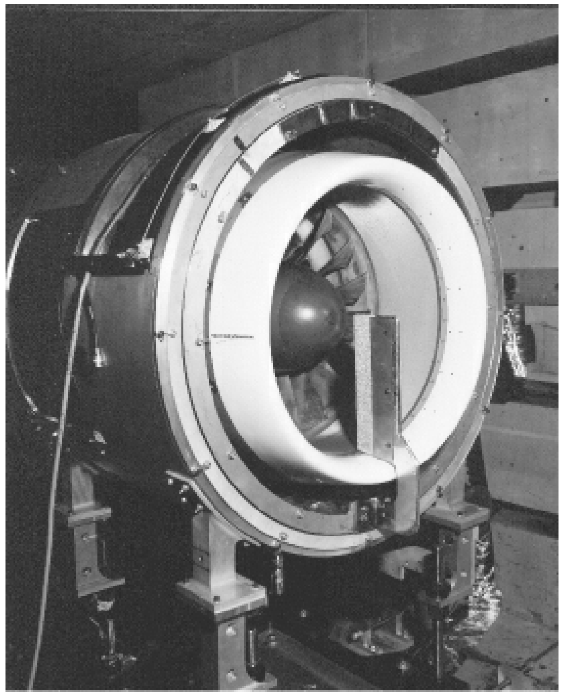


Figure 1. Photo of the rotating rake system installed on the inlet of Fan 1.

Figure 2. Photo of the rotating rake system installed on the exhaust of Fan 2.

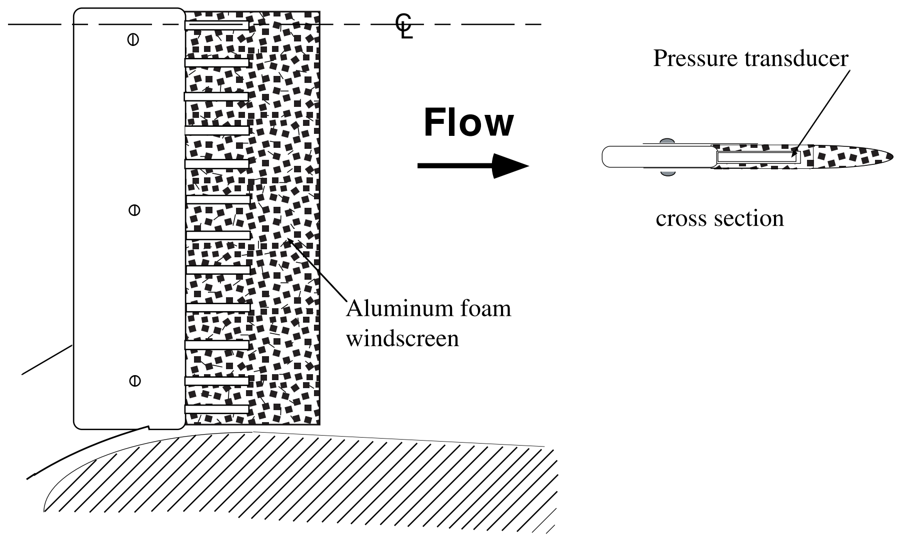
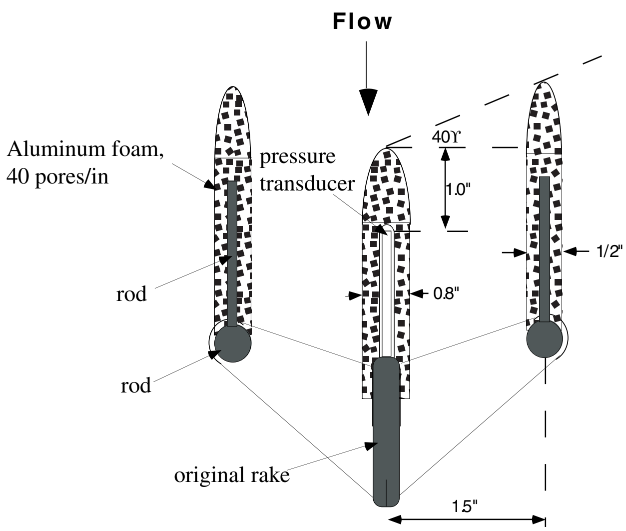


Figure 3. Inlet rotating rake and windscreen for 22" fans



a) Cross section

b) Photograph

Figure 4. Exhaust rake and windscreens for 22" fans

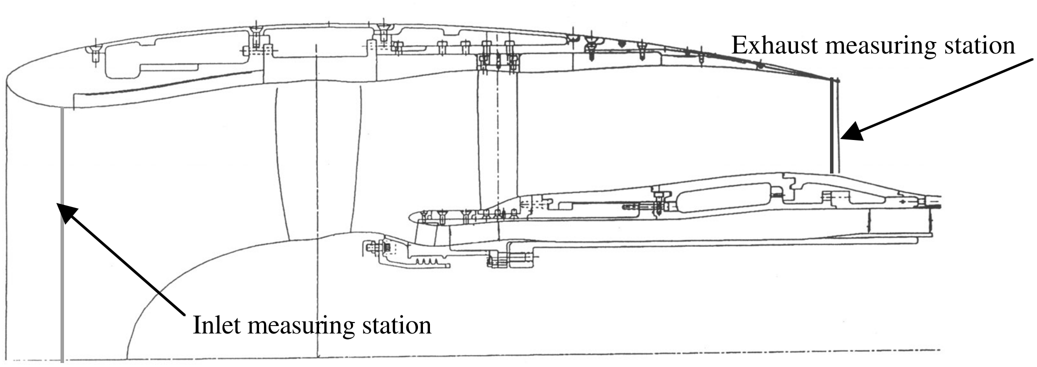


Figure 5. Sketch of fan showing mode measuring stations

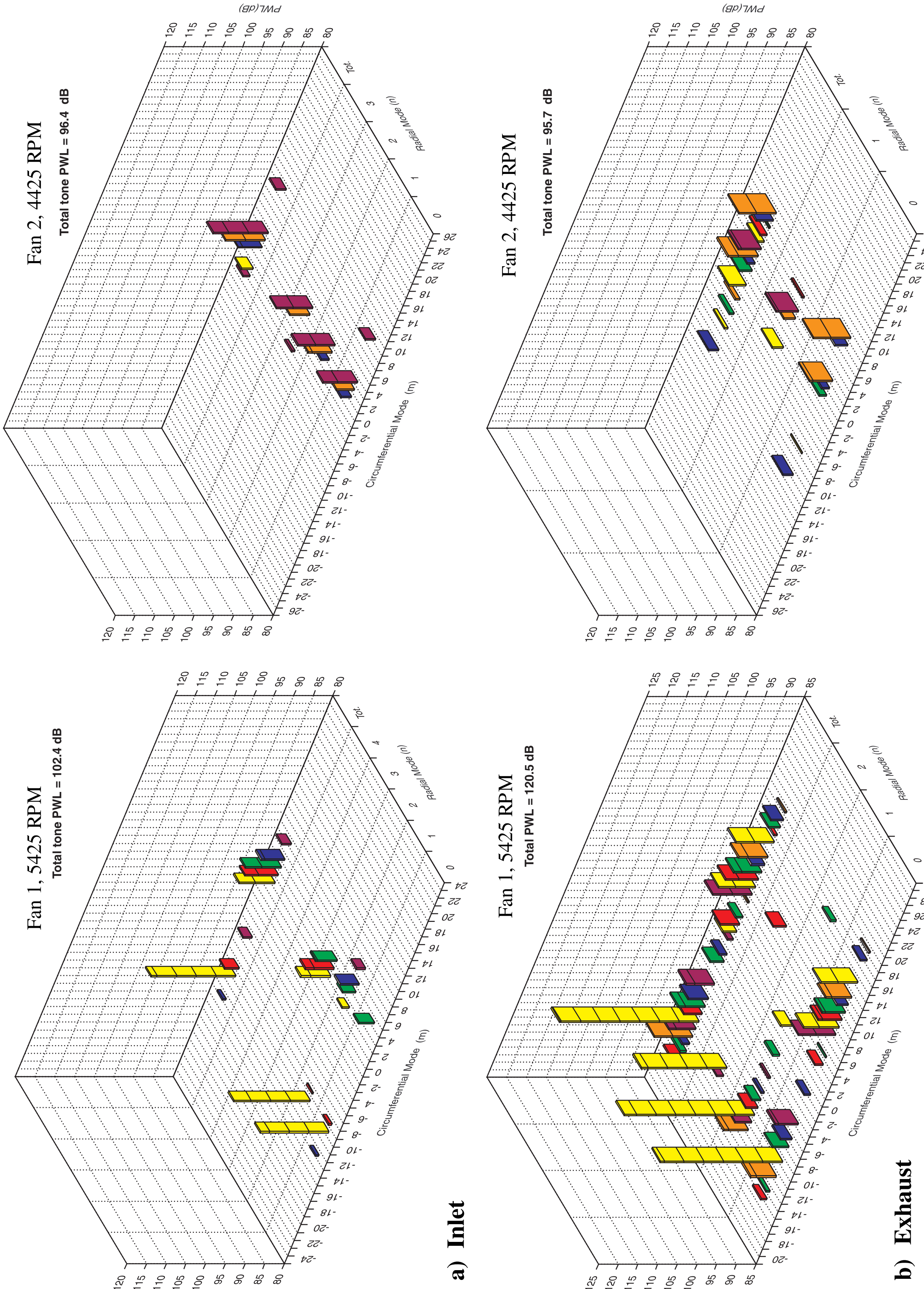


Figure 6. Comparison of the 2BPF modal structure of Fans 1 and 2 at approach power

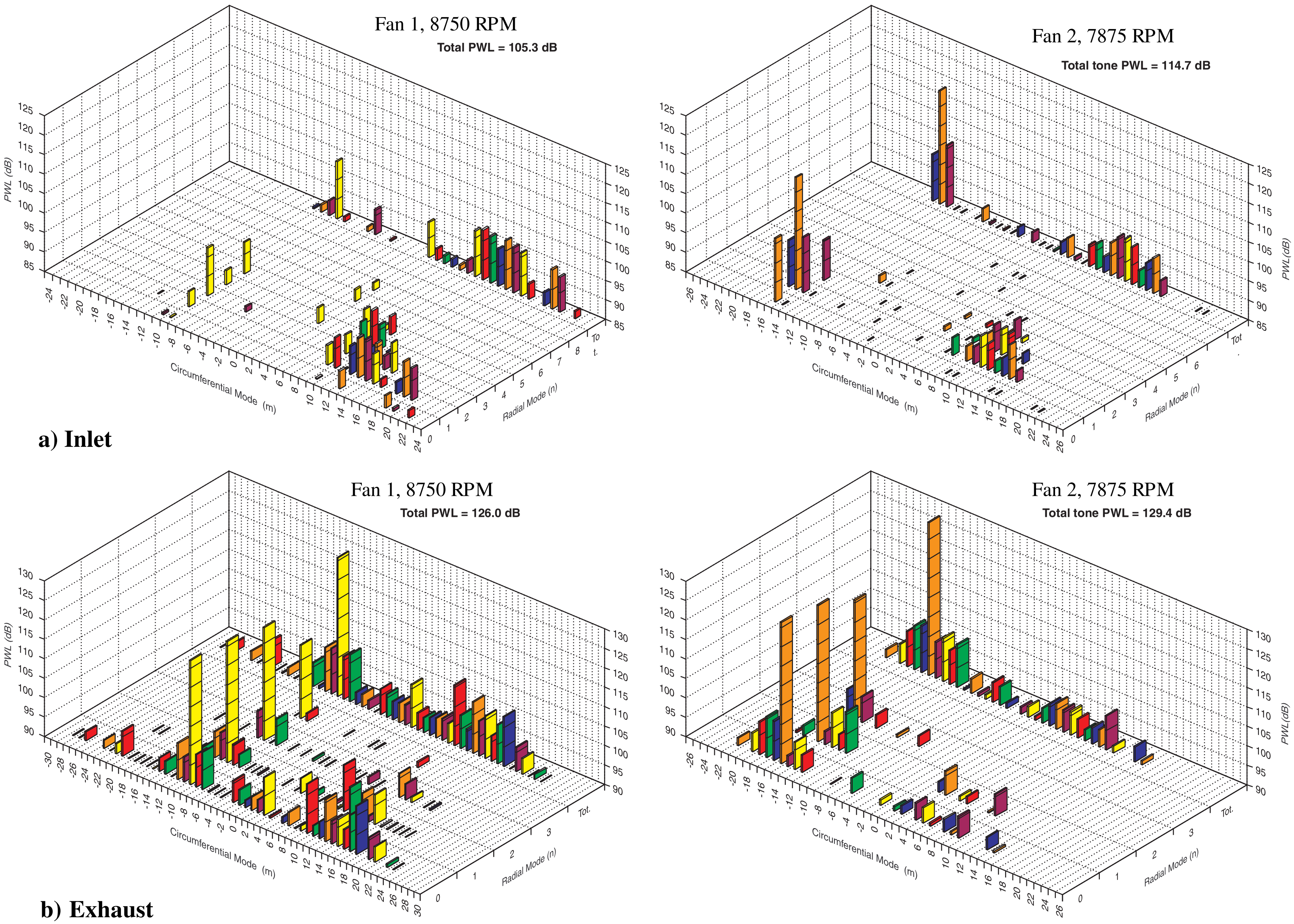
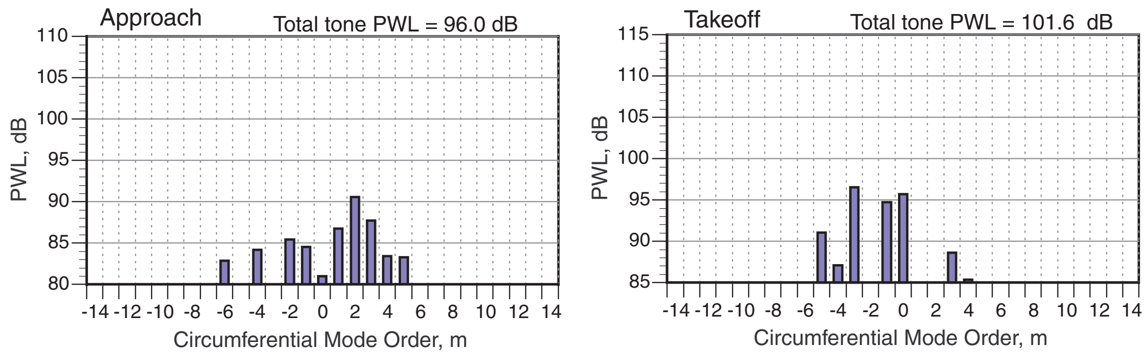
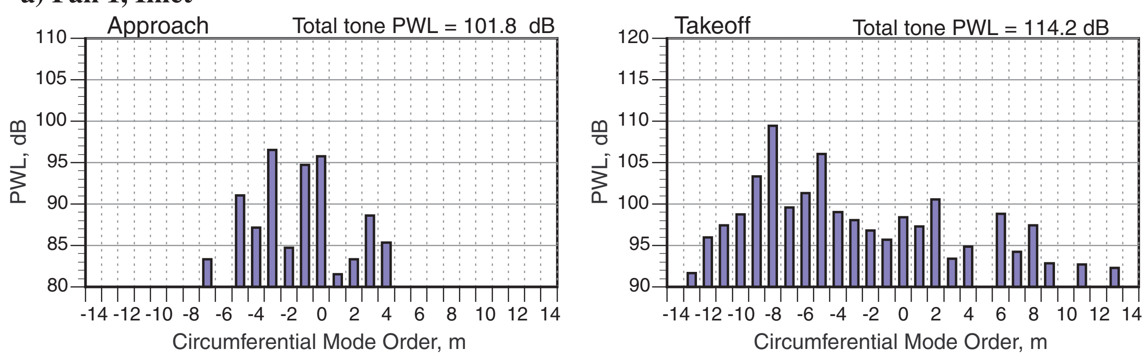


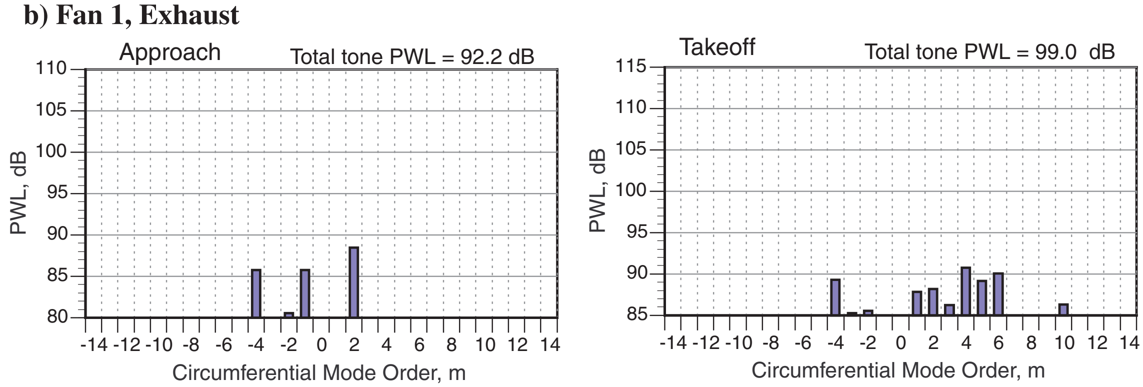
Figure 7. Comparison of the 2BPF modal structure of Fans 1 and 2 at takeoff power



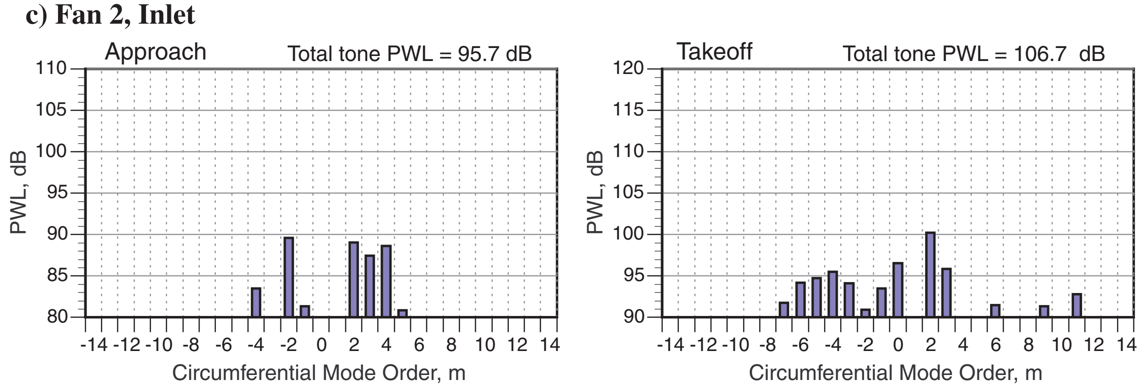
a) Fan 1, Inlet



b) Fan 1, Exhaust

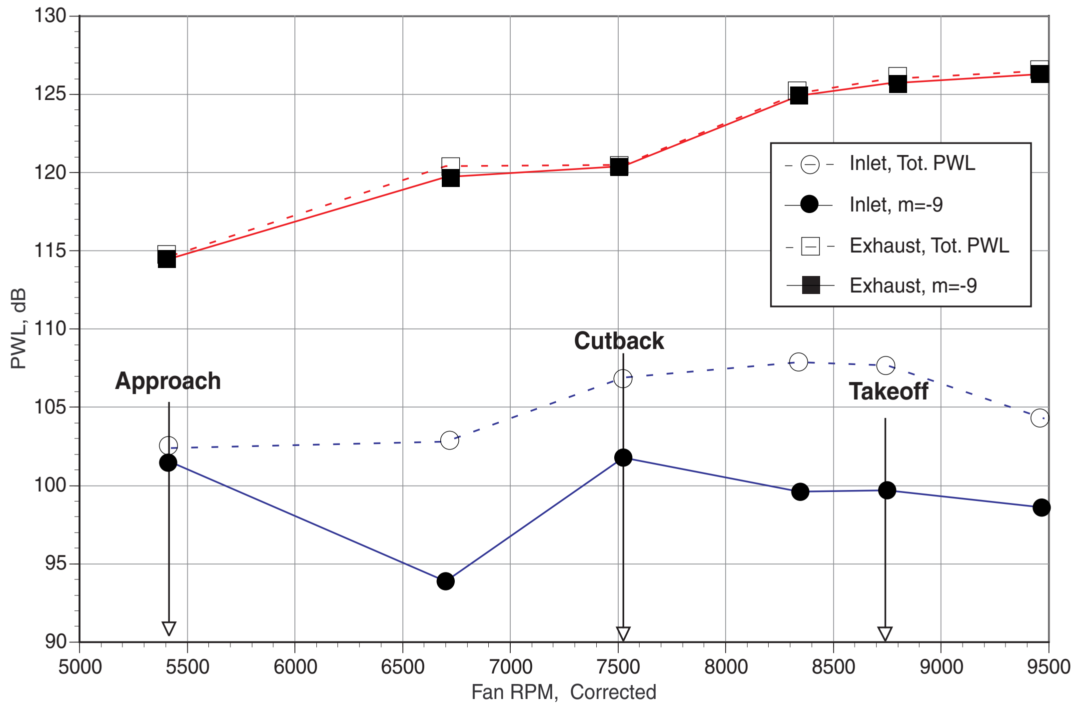


c) Fan 2, Inlet

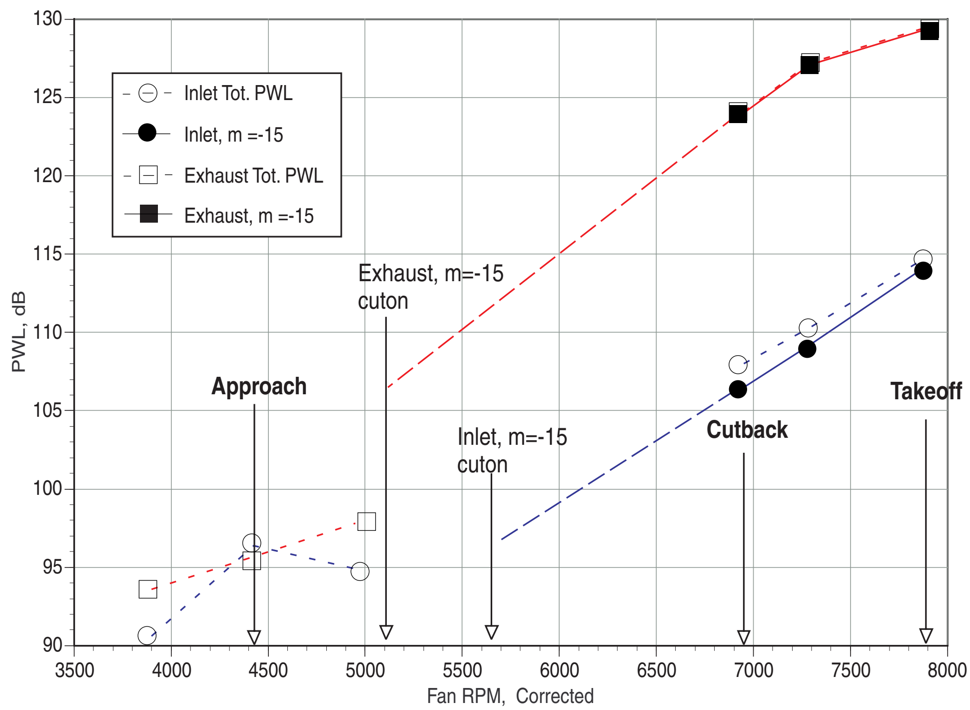


d) Fan 2, Exhaust

Figure 8. BPF circumferential mode power for Fans 1 and 2

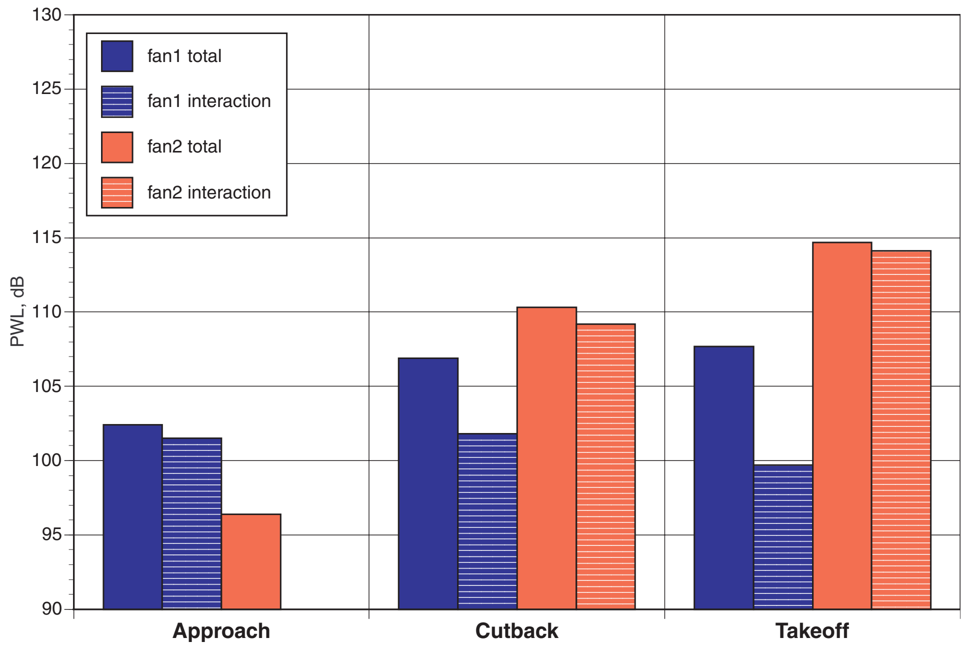


a) Fan 1

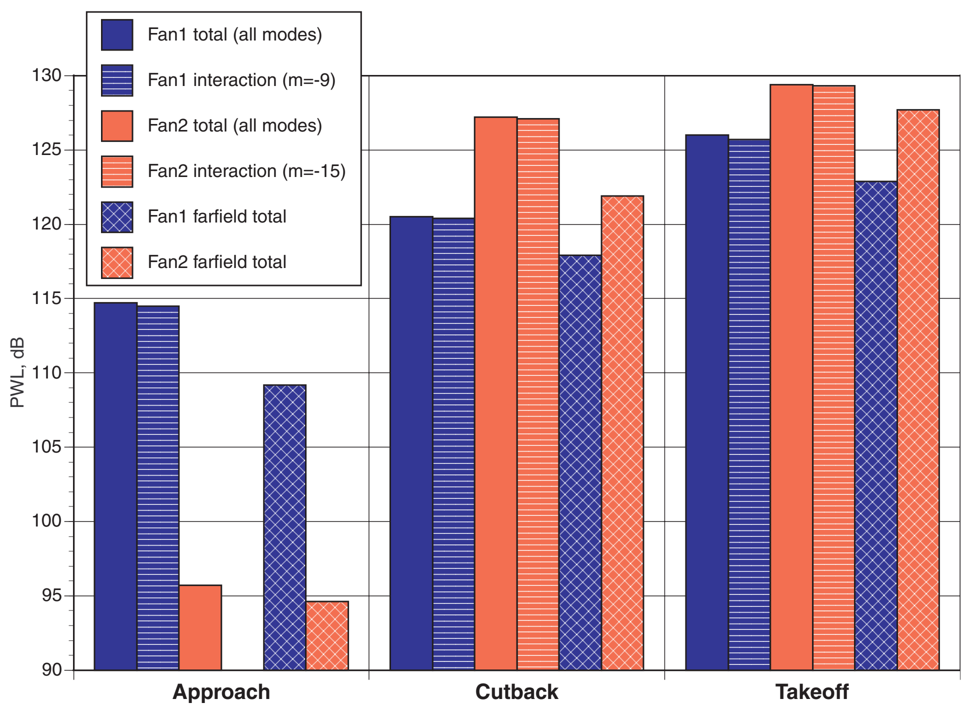


b) Fan 2

Figure 9. 2BPF interaction mode and total tone power as a function of fan speed for Fans 1 and 2



a) Inlet



b) Exhaust

Figure 10. Comparison of 2BPF interaction and total tone power for Fans 1 and 2

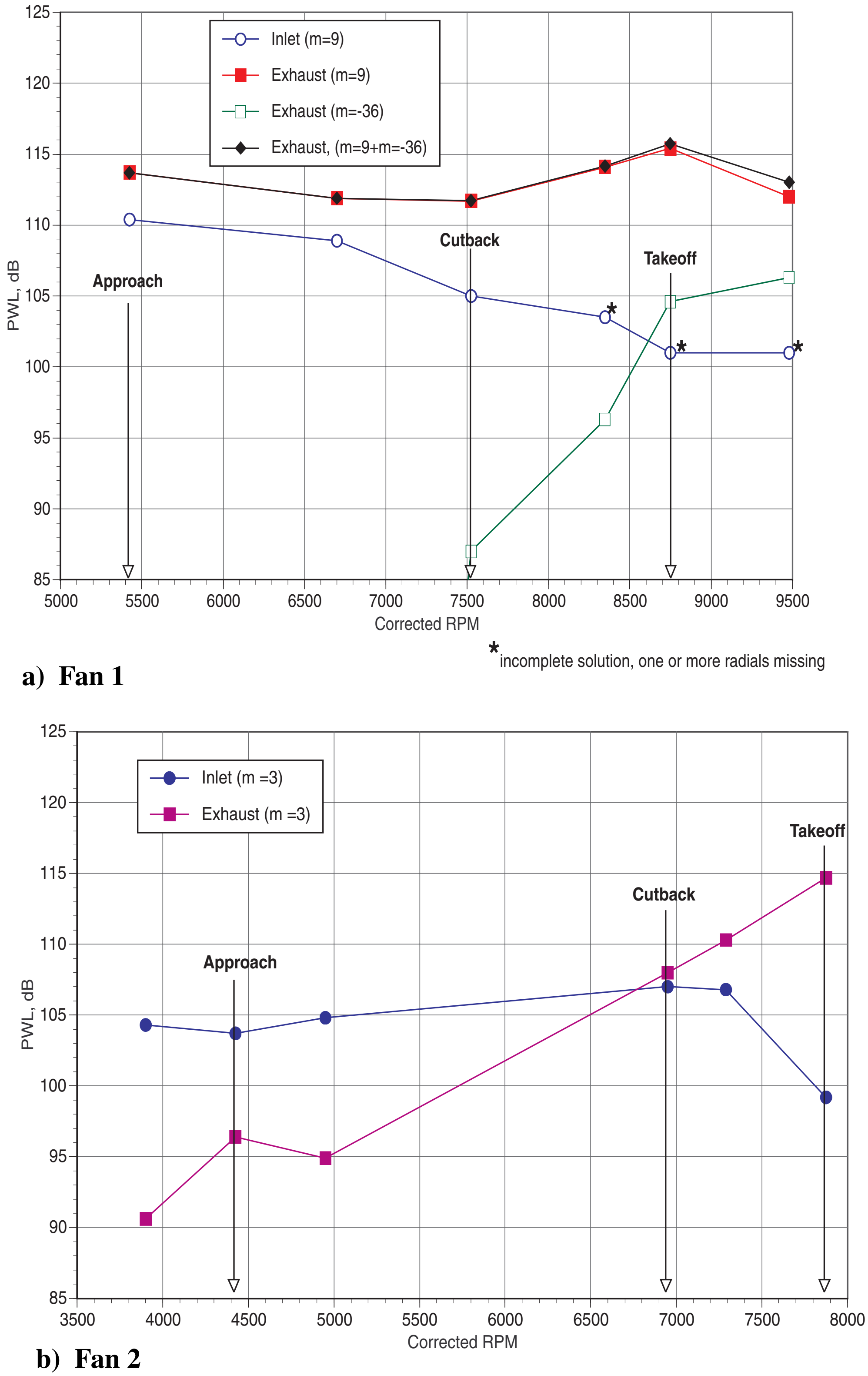


Figure 11. 3BPF interaction modes for Fans 1 and 2

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